Circulation, eddies, oxygen and nutrient changes in the eastern tropical South Pacific Ocean

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Reply to reviewer #2

Reviewer #2:

This paper aims at describing the circulation, oxygen and nutrient changes in the eastern subtropical South Atlantic from ship cruises, floats and historical hydrographic data. This is an interesting paper being the data set valuable and, in my opinion, explored in a convenient way adding new knowledge on the circulation variability in the region and related changes in oxygen and nutrients. My main concerns are the incomplete description of the eddy field south of the domain and the uneasy reading of some parts of the ms. Saying this, in general I think the paper should be published subjected to minor revisions as detailed below.

Answer to reviewer 2: We thank the reviewer for the good comments especially on the eddies, which helped to improve the manuscript during the revision. As the general comments (above) are specified in the detailed comments, we list our replies and changes made below.

We modified the manuscript considerably as explained below in the detailed comments.

Detailed comments:

Reviewer #2:

1) Page 2206, L24 'direct observations'. It would be preferable to use here and all long the text "in situ observations" instead of "direct observations"

Answer to reviewer 2: We changed ‘direct observations’ to ‘in situ observations’ for the CTD-oxygen measurements and ‘direct velocity’ to ‘ADCP velocity’.

In the revised ms we changed ‘direct observations’ to ‘in situ observations’ for the CTD-oxygen measurements and ‘direct velocity’ to ‘ADCP velocity’.

Reviewer #2:

2) Page 2207 L1-2. Please add references on HCS

Answer to reviewer 2: We added the reference Chavez et al. 2008, which was an overview for a special issue in Progress in Oceanography with several papers on the Humboldt Current system.

We included the reference Chavez et al. 2008 in the revised manuscript.

Reviewer #2:

3) Second paragraph page 2208. Mode water eddies are most commonly referred as Intrathermoclines Eddies or ITEs (Hormazabal et al., JGR, 2013 and references therein; McGillicuddy, JPO, 2015). Therefore I would change all long the text the term “mode water eddy” by ITE. Moreover I think that a short paragraph with the definition and references to ITEs should be added to the ms. In particular a brief description of South Pacific ITEs characteristics according to Hormazabal et al., (2013) should be also included. South Pacific ITEs have a minimum oxygen signal as it is also the case for the ITEs described in this ms. Therefore it cannot be argued that all eddy variability supply oxygen to the OMZ as claimed on L9-10 of this page.

Answer to reviewer 2: Both versions (ITE and mode water eddies) exist in literature. McGillicuddy 2015 (mentioned above) never uses the expression “Intrathermocline eddies” but only “Intrathermocline lenses” and McGillicuddy describes that mode water eddies as well as the reversal structure ‘cyclonic thinnies’ are created by eddy-wind interaction. As we used the expression mode water eddies in earlier publications and as it is also in the recent literature (McGillicuddy 2015) we prefer to keep the name ‘mode water eddy’ but explain the commonly used name ITE and reference the paper by Hormazabal et al., 2013.

A description of mode water eddies/ITEs, and the South Pacific characteristics according to Hormazabal et al. (2013) is now included (see below).

Right, the eddy variability either supplies oxygen or removes oxygen, this is now modified in the ms.

We explain in the revised manuscript the use of both expressions 'mode water eddies' and 'ITEs' in literature, and reference Hormazabal et al. 2013. With regard to a description of the eddies and the characteristics according to Hormazabal et al. (2013) we included: 'Mode water eddies (ITE's) consist of a bolus of fluid that depresses the main thermocline and raises the seasonal thermocline (McGillicuddy, 2015). In the South Pacific they are represented by subsurface lenses (~100 km diameter; 500 m thickness) of nearly homogeneous salinity (>34.5) and oxygen-deficient (<1.0 mL L-1) waters, properties linked to the equatorial subsurface water mass (ESSW) transported poleward by the Peru-Chile undercurrent (Hormazabal et al., 2013).'

In the revised text it is mentioned that eddy variability either supplies to or removes oxygen from the OMZ.

Reviewer #2:

4) First paragraph section 2. It is uneasy to read please rewrite annotating in Figure 1 the 86_W section, the 16_ 45' S section and indicating de location of el Callao.

Answer to reviewer 2: We modified the first paragraph of section 2 and subdivided it to better understand the work carried out. In figure 1 the 86°W section the 16°45'S section and Callao are annotated.

We modified the first paragraph of section 2 and subdivided it. In figure 1 we annotated the 86°W section, the 16°45'S section and Callao.

Reviewer #2:

5) First paragraph page 2. What is the distance between CTD stations along the different transects of M90 and M91 surveys? How it compares with the climatological first baroclinic Rossby radius of deformation (Chelton et al., 1998, JPO)

Answer to reviewer 2: The CTD station spacing was variable. For the open ocean sections the spacing was 0.5°. However, in the equatorial channel as well as on the near-shelf sections and the sections across the eddies the station spacing was reduced. Hence the distance is always

less than the first baroclinic Rossby radius of deformation as given in Chelton et al. 1998 (their figure 7).

We included in the text: ‘The CTD station spacing was 0.5° on the open ocean sections, but was reduced in the equatorial channel as well as for the near-shelf stations and the sections across the eddies.’

Reviewer #2:

6) Last paragraph page 2210. Please provide details about the uppermost bin depth and bin size for ADCP data.

Answer to reviewer 2: At most locations the bin-size of the 75 and 38 kHz ADCP measurement was 8 m with the first usable velocity depth at 21 m. Only on along-shelf sections on M91 and very short distances on 3 cross-shelf sections the ADCP setting was shifted to 4 m bin-size leading to a first reliable velocity at 13 m depth. As this does not influence the sections shown, only the information on 8 m bin-size and the first reliable depth at 21 m is presented in the revised manuscript.

We added in the text: ‘The bin-size of the 75 and 38 kHz-ADCP measurements was 8 m with the uppermost usable velocity depth at 21 m.’

Reviewer #2:

7) First paragraph page 2211. What was the nominal depth of CTD casts?

Answer to reviewer 2: Dependent on the time available, the nominal depth on the 86°W section in November 2012 was 1200 m, on the 16°45’S section 1500 m and on the cruise M91 in December 2012 2000 m when water depth was larger than 2000 m.

We included in the ms text: ‘Except for some deep profiles, the nominal sampling depth was 1200 m on the 86°W section, 1500 m on the 16°45’S section and 2000 m for the M91 cruise in December 2012 when off the shelf’.

Reviewer #2:

8) Page 2212, L17. “regular situation” what is the meaning for regular “averaged situation” “climatological situation”?

Answer to reviewer 2: Actually there are not enough observations to create averaged situations, hence the observations are compared to description in literature and this is now mentioned in the revised ms.

We modified the sentence to:’ However, there are differences compared to the distribution described in literature.’

Reviewer #2:

9) Page 2212, L18. Please change here and all along the text “density” by “potential? density anomaly” and temperature by potential or in situ temperature.

Answer to reviewer 2: We changed the wording in the entire text as proposed by the reviewer.

We changed the wording in the entire text from ‘density’ to ‘potential density anomaly’ and from ‘temperature’ to ‘potential temperature’ as proposed by the reviewer.

Reviewer #2:

10) Section 3. Includes both results and discussion please rename as “Result and discussion” and rename last section as “Summary and concluding remarks”

Answer to reviewer 2: We modified the 2 headings as proposed by the reviewer.

In the revised ms we modified the 2 headings as proposed by the reviewer.

Reviewer #2:

11) Section 3.1 first sentence. I miss a figure showing also the oxygen vertical section superposed to selected isopycnals together with the ADCP section along 86_Win order to support the eastward transport of rich oxygen waters and westward transport of low oxygen waters. Although further on the text oxygen transport is discussed and compared with climatological oxygen distribution on my opinion a detailed description of the velocity and oxygen field along 86_ W is needed in order to well establish the

oxygen transport related to the currents system. CTD stations location should be also included at the top axis of both plots.

Answer to reviewer 2: We added a figure 2b with the oxygen distribution and selected isopycnals for a direct comparison of the velocity field and the oxygen distribution and describe the higher oxygen values in the eastward current bands when compared to the westward SEC current bands.

CTD locations are marked only on figure 2b as this field is derived from the CTD profiles, while the velocity field in figure 2a is from the ADCP measurements. As the two figures are placed above each other the CTD locations should be also recognizable for the selected isopycnals.

We added a figure frame 2b below figure frame 2a with the oxygen distribution along 86°W with selected isopycnals and marked the CTD locations. For the oxygen supply we write: 'The eastward flow in the equatorial channel as well as the two SSCC current bands are connected to higher oxygen values compared to the westward SEC current bands with low oxygen at subsurface layers.'

Reviewer #2:

12) Second paragraph page 2213. The signature of the eddy field south of 15 _S need additional evidences from the potential density anomaly an oxygen fields. SSH provides only a snapshot for 21 November. For this day there is only visible the signal of an anticyclonic eddy south of the section without a clearly signal of cyclonic eddies. What were the time and dates to complete the section between 15_ S to 25_ S? As they are geostrophycally adjusted the eddies must have a signal in the potential density anomaly field. Please show a vertical section of this field from 15_ S to 25 _S superposed to the velocity field. Cyclonic circulation must coincide with a dome shape of the isopycnals in the case that the section has crossed cyclonic eddies. In the case of the anticyclonic eddy, as the authors indicates that it is an ITE type, isopycnals must show a dome shape in the shallower layers and bowl shape in the deeper layers. Moreover if it is the case, the oxygen section should show an oxygen minimum at the ITE core.

Answer to reviewer 2: The section was made only to 24°S and the time for the section between 15°S and 24°S was 3 days (15°S 10 Nov. 3:22 pm; 24°S 13 Nov. 5:52 pm). Additional isopycnals were included in the new figure 2b to make the density distribution of the eddies better visible. The eddy structure is now described in the text.

In the first submission we mentioned on page 2213 only an anticyclonic eddy, but did not specify it as an ITE.

We rewrote the text: 'Overlain on this westward flow are the signatures of two shallow cyclonic features at about 23.5°S and 18°S and a deeper reaching anticyclonic feature at about 22°S (Fig. 2), which are also visible in the sea level height anomaly of 10 to 13 November 2012 when the section south of 15°S was measured, and are still visible on 21 November (Fig. 1). The isopycnals show a dome shape and higher oxygen in the core of the cyclonic features and a bowl shape and lower oxygen for the anticyclonic feature centered at the location where the zonal velocity component reverses (Fig. 2).'

Reviewer #2:

13) Last paragraph page 2213. It is confusing and uneasy to read. This may be solved referring to a table including ship cruises dates and the corresponding EUC depth ranges and transports

Answer to reviewer 2: Actually there are only three transport values, probably too few for an own table. However, as there was a section on changes south of 15°S in-between the two EUC paragraphs and additional information on the connection of the EUC with the SICC, it was difficult to follow the transport discussion. We modified now the information by shifting the information on the region south of 15°S and on the connection to the EUC (see below), removed repetition of the upper 200 m layer information from the text and we think that the transport information should be now clear without an additional table.

We moved two paragraphs and connected the transport description parts, one in front of the EUC transport section and one behind the EUC transport section, hence it should be now clear which differences were observed.

Reviewer #2:

14) Page 2214, L11-12. Stramma et al. (2013) sampled a shelf break ITE in November 2012. In the December 2012 16 _S transect there are not evidences of the occurrence/persistence of such ITE (see comments 18 below). Moroever the ITE would cause a decrease of oxygen.

Answer to reviewer 2: Thanks, the sentence was misleading. Inspection of the figure 3a shows anticyclonic flow at 50 m depth with high oxygen around the core of the mode water eddy carrying high oxygen water from the open ocean, while in the center low oxygen was observed. This is now rewritten.

We modified the sentence to: 'Near 16°S high oxygen values at 50 m depth are related to water from the open ocean circulating around the anticyclonic eddy located near the shelf break at the end of 2012 (Stramma et al. 2013), while the low oxygen at 50 m marks the core of the mode water eddy.'

Reviewer #2:

15) Page 2214, L22-23. There are no evidences of an ITE in M91 16 _S section

Answer to reviewer 2: The statement was misleading. Described is the anticyclonic circulation centered south of 16°S in figure 3b, und this is modified in the revised version.

We modified the sentence to: 'The anticyclonic eddy centered south of 16°S is slightly lower in oxygen than the CARS-climatology and exhibits the reduced oxygen distribution in the mode water eddy at 200 m depth.'

Reviewer #2:

16) Page 2215, L10-13. As PCUC transports low oxygen it would be helpful for identify its signal to overlay selected oxygen contour lines in Figure 4 sections.

Answer to reviewer 2: We included oxygen contours in figure 4 and this provides some nice additional information included in the revised manuscript.

We modified figure 4 with smoothing the contour lines, adding a km-scale bar and including oxygen contours. The oxygen field is discussed in the revised text.

Reviewer #2:

17) Page 2215, L12. “The transports” please change as “The southeastward transports”

Answer to reviewer 2: The word southeastward was included.

We write now ‘the southeastward transport’ as proposed.

Reviewer #2:

18) Page 2215, L21-21. Here again the occurrence of an ITE along 16_ S in the December cruise is not well supported. ADCP section does not show any anticyclonic circulation. Moreover ITE located by Stramma et al. (2013) was along 16_ 45’W not at 16 _W and in the November cruise a not in the December cruise.

Answer to reviewer 2: As before, the statement to 16°S was misleading. The horizontal velocity distribution at different depths (Fig. 3) shows that the 16°S section is influenced by a strong northwestward flow component at the northern side of the eddy located to the south. Adding the oxygen distribution as proposed clearly helped to show the influence of the eddy. This is now modified in the revised text.

We modified the sentence to: ‘At 16°S the PCUC is weak with only 0.2 Sv near the shelf, as at that time a strong anticyclonic mode water eddy was located south of this section at the shelf (Stramma et al., 2013). The velocity components at different depths (Fig. 3) show that the 16°S section contains a strong northwestward flow component of this eddy and the oxygen distribution shows the low oxygen core at the flow reversal at the 16°S section.’

Reviewer #2:

19) Last sentence first paragrah page 2220. This sentence is too much speculative please read comment above

Answer to reviewer 2: With the additional oxygen section in figure 2 and the related discussion (as mentioned for comment 12) the presence of a mesoscale feature becomes much clearer and the sentence was modified to include this new information.

We rewrote this sentence: ‘The reversal between oxygen decrease and oxygen increase south of 18°S is in part related to the eddy activity in this region as can be seen in satellite sea level

height anomaly and the oxygen and density distribution in relation to the zonal velocity components (Fig. 2).'

Reviewer #2:

20) Last sentence page 2221. The temperature anomaly related with the ITE resemble to me very large, almost 300 km in diameter. Moreover there is no a corresponding negative oxygen anomaly. Have the authors checked the presence of this ITE in the 1993 ADCP and potential density anomaly sections?

Answer to reviewer 2: Reviewer 1 asked to remove this sentence on the mesoscale feature as the text is on the large-scale discussion of IPO and distracts from the important message. Therefore, we removed this sentence which helps to focus more on the new results.

We removed this sentence as it is not necessary for the large-scale description of the IPO.

Reviewer #2:

21) Last sentence first paragraph section 3.3. This sentence is too much speculative please read comment 18 above

Answer to reviewer 2: The last sentence of first paragraph section 3.3 is the same text as for comment 19 for the 86°W section and was discussed for comment 19. The mentioned comment 18 refers to the coastal sections and not the 86°W section and for this discussion please see our reply to comment 18 above.

We made the related changes as described for comments 18 and 19.

Reviewer #2:

22) Figure 4. Please include and scale bar in km

Answer to reviewer 2: A scale bar is included.

We modified figure 4 with smoothing the contour lines, adding a km-scale bar and including oxygen contours.

Reviewer #2:

23) Conclusions should be more concise clarifying the novels findings.

Answer to reviewer 2: The last chapter was rewritten to clarify the novel findings.

We modified the last chapter and removed the last paragraph of the first version, as this was only a summary of the paragraphs of the discussion and conclusion chapter.